The MUSES-CN Nanorover Mission and Related Technology*

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Abstract – Recent advances in microtechnology and mobile robotics have made it feasible to create extremely small automated or remote-controlled vehicles which open new application frontiers. One of these possible applications is the use of nanorovers (robotic vehicles with a mass of order 1 Kg or less) in planetary exploration.

NASA and Japan's Institute of Space and Astronautical Science (ISAS) are cooperating on the first mission to collect samples from the surface of an asteroid and return them to Earth for in-depth study. The ISAS MUSES-C mission will be launched on a Japanese launch vehicle in July 2002 from Japan toward a redezvous with the asteroid 1989ML in September 2003. A NASA-provided nanorover will conduct in-situ measurements on the surface. Asteroid samples will be returned to Earth by MUSES-C via a parachute-borne recovery capsule in June 2006. This paper describes the rover being created for this mission and related technology developments.

Table of Contents – This paper consists of an introduction, an overview of the rover mission on the asteroid, a discussion of the rover design and of the issues related to microgravity surface mobility, a discussion of the technology needed to address those issues, and conclusions.

Introduction

NASA and ISAS have agreed in principle to collaborate on the ISAS MUSES C mission for the mutual benefit of both space agencies. The collaboration includes a number of elements in addition to the existing MUSES C mission. Among these are that NASA will build and deliver to ISAS a rover to be used on the surface of the asteroid and that ISAS will deliver the NASA rover to the asteroid. Science investigators from both countries will participate in the mission operations and data analysis for both Spacecraft and Rover instruments. The ISAS MUSES C mission is fully described in references 1 - 4.

NASA and ISAS will cooperate on several aspects of the mission, including mission support and scientific analysis. In addition to providing the rover, NASA has arranged for the testing of the MUSES-C re-entry heat shield at NASA/Ames Research Center, and will provide supplemental Deep Space Network tracking of the spacecraft, will assist in navigating the spacecraft and provide arrangements for the recovery of the sample capsule at a landing site in the U. S. Scientific co-investigators from the U. S. and Japan will share data from the instruments on the rover and the spacecraft, and will collaborate on the investigations of the returned samples.

With a mass of about 1kg, the rover experiment will be a direct descendant of the technology used to build the Sojourner rover. The rover will carry three science instruments: a visible imaging camera, a near-infrared point spectrometer and an alpha X ray spectrometer. The solar-powered rover will move around the surface of 1989ML collecting imagery data, which are complimentary to the spacecraft investigation. The imaging system will be capable of making surface texture, composition, and morphology measurements at resolutions better than 1 mm. The rover will transmit this data to the spacecraft for relay back to Earth. Due to the microgravity environment on 1989ML, the rover has been designed to right itself in case it flips over. Solar panels on four sides of the rover will ensure that enough power will always be available to the rover to activate the motors needed to turn over. Posable struts will allow the rover to position its chassis such that the camera can be pointed straight down at the surface or straight up at the sky.

MUSES CN Project

NASA has asked JPL to implement the NASA portion of the collaboration on MUSES C. At JPL, the MUSES CN [N for NASA] project has been established for this purpose. At JPL the MUSES CN activities fall into three technical areas: 1) science, 2) mission support and 3) rover development/operations. This paper focusses on the third area.

MUSES-CN Mission overview – The MUSES-CN rover mission begins when the rover (Figure 1) is ejected from the MUSES-C spacecraft onto 1989ML. The nominal characteristics of 1989ML are presented in table 2. The nominal mission parameters are presented in table 3. Prior to release, the solar-powered rover sits inside the Orbiter-Mounted Rover Equipment (OMRE). While attached to the

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spacecraft, the rover is shielded from the Sun. The OMRE is the rover's interface to the spacecraft and contains an antenna/receiver for rover-to-OMRE communication and a data line for data transfer. The rover will transmit 2 Mb of data per day on average to the spacecraft. These science and engineering data and will be compressed appropriately in consultation with the engineering and science teams.

Once the rover is dropped from the spacecraft, it is expected to bounce a few times before coming to rest on the surface. The concussion of hitting the surface at 1 cm/sec after falling from 10s of meters of height in the micro gravity environment of 1989ML is no more than falling a few millimeters on Earth. The rover will then orient itself. Due to the low-gravity environment, the maximum speed the rover can travel is about 1.5 mm/sec without losing surface contact. The rover has been designed with the capability to right itself if it flips onto its back. Since the four posable struts are independent, the rover can be commanded to point itself in any orientation. A pointable mirror and actuated focus mechanism allow the rover to take panoramic images as well as microscopic ones.

Table 1. 1989ML Nominal Characteristics

Property	Value
Absolute Magnitude	19.5
Albedo Limits	0.04 - 0.15
Effective Radius (km)	0.2 - 0.4
Bulk Density (g/ cc)	1 - 4
Rotation Period (hrs)	19
Spectral Class	Xc
Escape Velocity (m/sec)	0.15 - 0.60
Surface Velocity (cm/sec^2)	$(0.6 - 5.0) \times 10^{-2}$
Perihelion (AU)	1.10
Aphelion (AU)	1.45
Orbital Period (yrs)	1.44

The primary rover science objectives are to carry out scientific measurements with its entire instrument suite and to transmit the data before asteroid "night," at which time, the rover will shut down until sunrise. There is little non-volatile storage on the rover. Most data not transmitted to the orbiter at the end of the daily investigation schedule will be lost. Daily investigations include visual imaging of the terrain and targets of interest, point spectra in the infrared, AXS spectra, and soil mechanics investigations using the rover as an instrument.

Understanding the orientation of the rotation axis of the asteroid with respect to the Sun will be critical for rover placement on the surface to ensure maximum operational periods. As a technology experiment, the rover is being designed with the capability to "hop" in low-gravity. If the experiment is successful, the rover may be able to transverse long distances [10 - 100 m's]. This behavior may enable the rover to stay in the Sun longer to take more data and avoid thermal cycling. The rover will try to reach and look inside one or more of the craters left by a sampling event to ascertain stratigraphy which will be lost in the collected sample. The rover will also seek evidence for sample modifications due to the impact process. The nominal rover mission ends when the orbiter departs 1989ML.

Table 2. Mission Operations at 1989ML

Mission Phase	Dates	Period weeks	Sun (AU)	Dist (km)
Initial Acquisition and Margin	October 20, 2003- November 2, 2003	2	1.11	20–50
Mapping	November 3, 2003 - December 14 2003	6	1.11	20
Sampling and Rover Deployment	December 15 2003 - January 15, 2004	4	1.1	0 – 20
Extended Science	January 16, 2004- April 14, 2004	13	1.7	0 – 20
Leave 1989ML	April 15, 2004		1.33	----

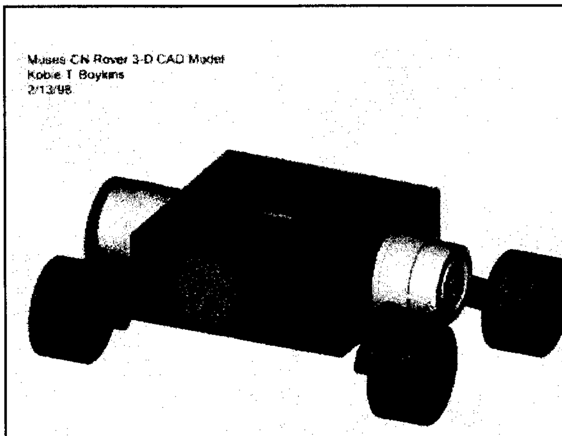

Figure 1. MUSES-CN Rover

The MUSES CN Rover

The MUSES CN rover[5] is a direct descendant of the technology used to build the Sojourner rover used on the Mars Pathfinder mission, while being 10 times less massive and including more capability for scientific measurements. The total mass allocated by ISAS for the NASA payload is only 2.7kg. The MUSES CN rover is an experiment of rover mobility and miniaturization first and an enabler of science measurements second. This order of objectives is similar to the Pathfinder Sojourner rover

The key rover characteristics are listed in table 3. Note that while the rover itself is only about 1300g the remainder of the 2700g allocation is consumed by the Orbiter Mounted Rover Equipment [OMRE] located on the MUSES C spacecraft. The OMRE provides the following functions: 1) thermal control of the rover during cruise, 2) mounting the rover to the spacecraft during launch and cruise, 3) ejecting the rover off the spacecraft at the asteroid, 4) transmitting commands from the orbiter to the rover, 5) receiving data from the rover and transmitting it to the orbiter for re-play to Earth and 6) housing OMRE computer.

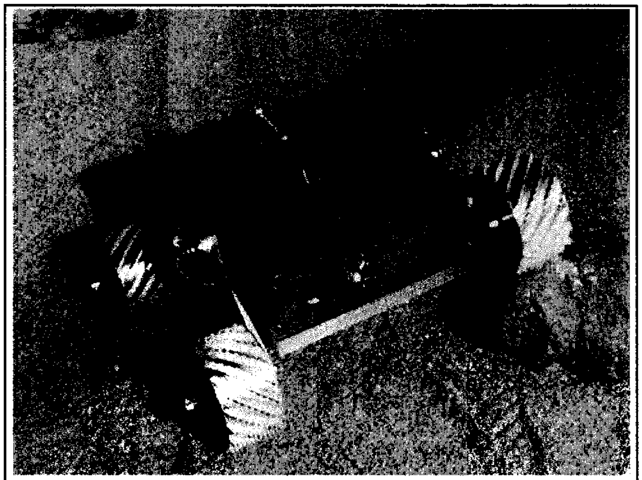

Figure 2. MUSES CN Rover Prototype

Table 3 Rover Characteristics

Rover Characteristic	Value
Mass	1300 grams
Size	14 x 14 x 6 cm
Power Capability	2.3 W (normal incidence)
Max. velocity, rolling contact in microgravity	1.5 mm/ sec
Data rate [quoted at 20km range to OMRE receiver]	4700 bits per second effective rate (9600 baud raw data rate)

The rover consists of a rectangular body, which is 14x14x6 cm in dimension with four wheels on four posable struts for mobility (see

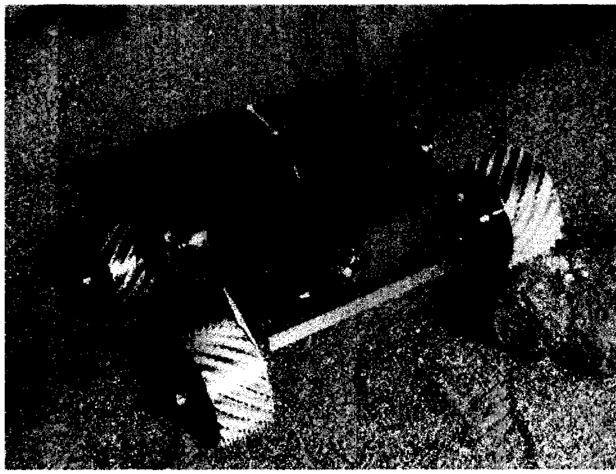

Figure 2). The wheels are 6.5 cm in diameter, mounted on struts, which extend in pairs from hubs emerging from the geometric center of two opposing 14x6 cm faces of the body. Each strut is 7 cm long from the center of their pivot to the center of the wheel axis. Four of six faces of the rover body have solar cells for power generation. The top face also has the antenna element needed to transmit the radio signal. The rover can communicate as long as it is powered and has a direct line-of-sight to the OMRE located on the MUSES C spacecraft.

The rover has optical detectors on all six orthogonal exterior faces of the rover. Using these detectors, the rover will be able to determine the direction to the sun. Vertical sensing is not possible due to the unavailability of accelerometers which can measure the microgravity fields of asteroids and yet fit within the mass constraints of the rover. The rover has a laser range finder, which enables it to determine the range to nearby objects. This serves a similar function to the mast-mounted stereo lander cameras used in conjunction with the Sojourner rover to localize the 3-D positions of science and engineering targets, hazards, and other objects.

The rover carries three science instruments, the visual camera, the near infrared spectrometer and the alpha X ray spectrometer. The location of these instruments inside the rover is shown in figure 4. The functional performance of these instruments is presented in tables 4, 5 and 6. There is view window on the front face for the camera and IR spectrometer. The AXS sensor will open out to the rear of the rover and be placed in contact with rock or regolith by appropriate body/strut motion.

The entire rover system is being qualified for the temperature range of -180C to +110C, which is derived from the worst case situations during the mission. The mechanical environment for the rover is dominated by the vibration environment imposed by the ISAS MV launch vehicle. The MV is an "all solid" design and, as such, provides a relatively "rough ride". To be conservative, the mechanical elements of the rover are being designed to 100Gs and the OMRE to 125Gs. The entire rover is also being designed to be compatible with a radiation dose of about 25krad, although many components will tolerate much higher levels.

Electronics Subsystem – The flight electronics are based on the Synova R3000 32-bit flight processor, fabricated on the Honeywell Rad-Hard Foundry production line, and a radiation hard custom gate-array. In addition, 2Mbytes of rad-hard RAM and 1Mbyte of rad-hard EEPROM are provided. The radiation hardness of the processor and memory parts easily exceeds the expected worst case environment of about 25 krad. The electronics I/O includes the camera interface, control of ten 3-phase brushless cryovac motors, an IR Spectrometer and Alpha-Xray-Spectrometer, and general-purpose digital and analog I/O. Since, in the microgravity environment, the rover must accelerate smoothly to a speed of only about 1 mm/sec if it is to maintain rolling contact with the surface, the motors must be capable of moving extremely slowly. Also, one of the key technology experiments is to allow the rover to "hop" over the surface of the asteroid, which may require the wheels and struts to be capable of speeds of 20 cm/sec. To accommodate this range of motor velocities, a 3-phase pseudo-sine-wave controller, which is capable of actuating over a 3000:1 dynamic range, is being used. Using a 32-entry lookup table approximation to a sine wave, the rotors of each motor can be stepped into any of 32 angular positions. Each gearmotor has a 256:1 gearhead, so that the output shaft can be stepped in more than 8000 increments. The electronics will be implemented using double sided "chip on board" packaging in order to save mass and board area. The OMRE electronics will be very similar to the rover electronic in implementation and functionality. The OMRE electronics will not have as many motor drivers or EEPROM but will have some additional functionality in order to interface successfully to the MUSES C spacecraft data and power subsystems.

Power Subsystem – Because the mission environment is so very cold, there is no battery in the rover: it is powered only in direct sunlight. During periods of eclipse it hibernates, and recovers its state upon reawakening based on information stored in the EEPROM as well as communication with Earth. In sunlight, the rover is powered by the solar cells, which cover the top, bottom, front and back panels. The solar cells are planned to be state of the art multijunction cells with an efficiency of about 25%. A coverglass with an anti-reflective coating will be put on each cell. Diodes will be provided for each string to protect against shadows. The solar cell strings will produce power between 12 and 30 volts, depending on temperature and load. The maximum power produced by the main panel after radiation exposure and at the high end of the temperature environment is expected to be about 2.5 watts at 1.1 AU.

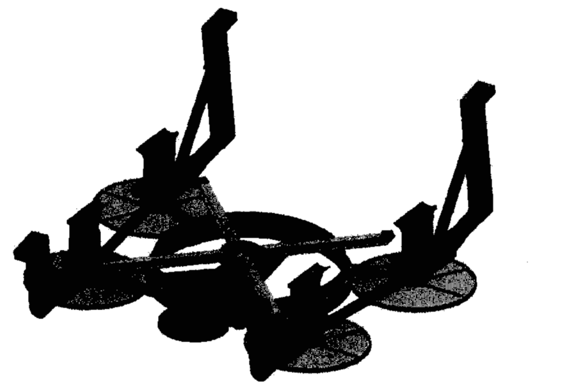

Figure 3. MUSES CN OMRE

Mechanical Subsystem – The rover mechanical subsystem is functionally centered around the optical bench. The optical bench is made of two panels of aluminum alloy between which the following assemblies are mounted: gimbaled mirror, camera/filter wheel, IR spectrometer, fold mirror/headlamp and the alpha X ray spectrometer. The mechanism for actuating the loupe lens is mounted to the top side of the optical bench. The electronics board will be mounted on standoffs to the top optical bench panel while the radio board will be mounted to the lower optical bench panel. The motors for the rover have been specially developed for this application. The motors are 3 phase, brushless DC with a specified torque of 1in-oz and a life requirement of 1000hrs within a temperature range of –200C to 125C. The mass of one motor including its gearbox is 10 grams. Each strut has 2 motors. One motor drives the wheel on its axis and the other motor drives the strut around its hub. The wheels are a complex assembly of thin conductors and insulators designed to function both as a mechanical wheel and as a proximity sensor to the asteroid surface. The shoulder hub includes potentiometers for position information. The top, bottom and side panels are also the substrates for the solar cells. The side panels are connected to the optical bench and act as radiators to help provide a suitable temperature environment for the instruments held between the optical bench panels.

Communications Subsystem – The MUSES-CN radio is a time-division duplex, L-band (1900 MHz PCS), radio transceiver operating at 9600 symbols per second utilizing non-coherently demodulated, Manchester-coded, binary frequency-shift keying. The maximum power consumption is 750 mW from a single +5 V dc bus. The radio is implemented primarily with commercial GaAs packaged parts for radiation hardness and will be mounted on a single board. Several radio functions such as clock recovery and Manchester decoding are being implemented in a radiation hard FPGA. The rover antenna is a right-hand circularly polarized square patch with an offset-pin feed, fired upon a high-k ceramic substrate. The rover radio communicates to an identical radio located in the OMRE on board the MUSES C spacecraft.

Optical Subsystem – The optical subsystem of the MUSES CN rover consists of a camera and an IR spectrometer, as shown in Figure 4. A three-position focus camera will be used with a gimbaled mirror to allow the rover to point the camera to areas that are in focus, instead of focusing on areas that happen to be on a fixed camera pointing axis. This approach also enables convenient acquisition of panoramic mosaics and it gives all the benefits of boresighting the spectrometer with the camera without any of the associated complexity. The nominal focus range is at about 6 meters. Two closeup lenses may be mechanically inserted into the optical path to change the focus position to 2 meters and 70mm for extreme closeup images.

The pointable mirror is an optical flat elliptical mirror mounted in a two-axis gimbal. A small permanent magnet is affixed on the back of the mirror. Coils of wire are wound around the gimbal assembly so that there is a symmetric pair of coils for each of three orthogonal axes. When current flows through the coils (windings on the same axis are wired together so that there are effectively only three coils) a magnetic field can be applied in any direction to the permanent magnet on the mirror. The permanent magnet will try to align with this applied field, rotating the mirror in the gimbal to any desired orientation. No encoding or other feedback from the gimbal is required, as the coarse position of the mirror can be assumed to be in alignment with the applied field and all fine-positioning information will be derived from camera images taken through the gimbaled mirror. The gimbaled mirror looks out through an optically flat window on the front of the rover to allow looking anywhere up to 30 degrees off-axis. The gimbaled mirror can be used to direct light from a wide variety of pointing directions either into the camera or into the IR spectrometer.

The visible camera is a 256x256 Active Pixel Sensor (APS) with a custom 30 mm F2 triplet achromat lens. A dichroic mirror folds the optical path from the nominal horizontal transverse axis shown in Figure 3 to a vertical axis down to the APS detector. A filter wheel with 9 filter positions lies between the APS detector package and the dichroic mirror. Infrared light passes directly through the dichroic mirror while visible light is reflected into the camera. Each pixel in the APS detector is 11.9 microns square. The quantum efficiency, including fill factor, is about 15% and has a well depth of about 40,000 electrons. The field-of-view of the camera is 0.1 radians and the resolution is 0.4 mrad/pixel. Using the gimbaled mirror, a complete 1 radian square mosaic is a 10x10 array of images.

A ranging sensor is included to measure the distance to candidate science targets on the asteroid's surface. A boresighted laser diode in the camera assembly gives a ranging sensor, which will give the needed accurate range data out to about 10 meters. The infrared laser light passes through the dichroic mirror, (which transmits about 90% and reflects 10% of the light at the laser wavelength but is essentially 100% reflective over the shorter wavelengths of the visible spectrum) and is collimated by the lens to a parallel beam over the 15 mm aperture. This beam produces a 15 mm spot on any terrain it encounters, which can be imaged by the camera. Since the spot is of fixed and known size, its apparent size in the image determines uniquely the range of the terrain at that spot. The smallest spot, which can be measured accurately, is about 3 pixels across; the 15 mm beam subtends 3 pixels at 12.6 meters. The spot diameter can be measured to about 0.1 pixels, so the ranging sensor is accurate to about 3% at 12.6 meters and 1% at 5 meters.

Because the spot size is fixed at 15 mm independent of range, the amount of sunlight, which falls on this spot, is also fixed. At 1 A.U. from the sun (a worst case for most small body missions, and slightly more than for 1989ML) the sun delivers 250 mW onto this same spot. An appropriate filter in the camera filter wheel can reject about 90% of the sunlight while still passing the laser light over the entire operating temperature range of the rover (the laser wavelength changes about 0.3 nm per K, so a filter width of about 100 nm is needed to accommodate the -125C to +125C design operational range). Thus the laser spot will be almost 10 times as bright as the sun if the terrain is at normal incidence to the beam, but grazing incidence will be common. To deal with this case, image differencing will be used as it was on Sojourner, where an image with the laser off is subtracted from an image with it on, leaving an image of the laser light plus noise.

Mobility Subsystem - The mobility subsystem of the rover (the four wheels, four struts) is designed to support nominal mobility and body-pose functions in full Earth gravity for testing and also designed to enable significant hops in the expected worst-case microgravity environment of 8 to 80 μg of surface acceleration and an escape velocity of about 15 - 105 cm/ sec. The rover mobility system will maintain the mechanical configuration of the rover if power is lost. The rover chassis is based on the "posable strut" chassis concept for a self-righting and/or upside-down-operable articulated vehicle. It includes the ability to recover from overturning as well as body pose control for camera/instrument pointing. Operation in extremely low gravity is accomplished since no free pivots are used (which would have too much friction to articulate freely in a microgravity environment.

Each strut/wheel assembly will also include a sensor to infer that the wheel is in contact with the terrain. This sensing will be used to allow the vehicle to roll on four wheels (instead of just three, which would be the natural state for a four-wheel vehicle without a passive suspension), to detect when one of the wheels has encountered an obstacle, to allow the vehicle to "hop" with all four wheels pushing so that no significant angular momentum is induced into the body, and to anticipate contact a fraction of a second before landing at the end of a hop.

The surface gravity on 1989ML is expected to be 8 to 80 μg and the escape velocity will be 0.2 to 1 m/s. With this low gravity, the gravitational force on a 1300-gram rover would be less than 0.13 grams of force. Depending on the model used for the surface properties of the asteroid, this low, normal force could imply certain mobility problems for conventional wheeled vehicles. If the surface is modeled as having conventional friction (e.g. coulombic friction), then the mobility characteristics of a vehicle in the asteroid environment will be a slow-motion version of the dynamics of an off-road vehicle on Earth. If the vehicle hits a 0.5 cm bump on the surface of the asteroid, computer simulations show that it will go more than one vehicle length into the sky and frequently overturn. For this reason, as well as the desire to be ejected from the host spacecraft at an altitude of a few tens of meters, the rover has been designed to be self-righting and to be able to operate upside down.

For precise motion of the rover to nearby target locations, the rover will roll slowly. Fine positioning of the rover will be accomplished by normal rolling motion at slow speeds of 1.5 millimeters per second or so. At these speeds it is believed that the gravity force (20 microgee nominal) and other forces (e.g. Van der Waal's, electrostatic) will allow the rover to maintain at least two wheels in contact with the terrain at all times. With contact sensing, the odometry for those wheels which are instantaneously in contact should be quite accurate (~5%). This accurate odometry, together with heading information derived from the sun will allow relatively precise, but slow, motion to selected targets on the surface. For longer-range mobility, hopping or jumps may be implemented.

Conclusions

NASA and ISAS are committed to collaboration on the ISAS MUSES C mission. The collaboration significantly benefits both space agencies. The collaboration includes science, mission support and hardware delivery/operations. ISAS's MUSES C mission is the first asteroid sample return mission and NASA's MUSES CN mission is the first mission to operate a vehicle in the micro gravity environment of a small body. The MUSES CN rover will be 10 times less massive that the Pathfinder Sojourner rover and will carry more science instruments. The MUSES CN rover will be able to roll, hop and right itself in the micro gravity environment of an asteroid.

Both the MUSES C and MUSES CN missions have aggressive technology demonstration objectives as well as enabling many important science investigations into the nature and origin of asteroids, the most important of which is the acquisition and return to Earth of a sample of a near Earth asteroid. In addition to the technology and science aspects of the missions, it is anticipated that the MUSES C and MUSES CN missions will attract a good deal of attention from the public and media in both countries. The extensive collaboration between NASA and ISAS on MUSES C will provide experiences upon which both space agencies can build for future possible collaborations on planetary missions.

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Biographies – Brian Wilcox is the MUSES-CN Rover Manager and the Supervisor of the Robotic Vehicles Group at JPL. Mr. Wilcox has an M.S. in Electrical Engineering from the University of Southern California and a B.S. in Physics and a B.A. in Mathematics, both from the University of California at Santa Barbara. He is the recipient of the NASA Exceptional Engineering Achievement Medal in 1992 for his work in planetary rover technology development and the JPL Exceptional Achievement medal in 1999 for the miniature Mars Ascent Vehicle concept which JPL Director Ed Stone described as "enabling Mars Sample Return".

Ross Jones is the Manager of the MUSES CN project at JPL. Mr. Jones has a B.S. degree from Purdue University and a M.S. degree from Massachusetts Institute of Technology, both in Aeronautical and Astronautical Engineering. Previous to the MUSES CN position, Mr. Jones was the supervisor of the Advanced Flight Systems Group in the

Mission and System Architecture Section at JPL. Mr. Jones has also worked in the Mission Design Section and Power Systems Sections at JPL. Mr. Jones was also instrumental in the creation of the concept of microspacecraft for planetary missions in 1988. Mr. Jones has authored 20 papers on various aspects of advanced mission and technology concepts for planetary exploration.

Table 4 Rover Camera Functional Performance

Parameter	Requirement	Desired	Current rover design
Spatial resolution on local surface having infinite contrast	<1 cm/pixel with at least 5:1 contrast ratio between adjacent pixels	<1 mm/pixel with 10:1 contrast ratio between adjacent pixels	0.047 mm/pixel with 70 mm closeup lens; much better than 10:1 contrast
Useful Depth of Field (at better than 1 cm/pixel spatial resolution)	0.1 m to 10 m	0 - infinity (<1 cm ground resolution or 1 mrad/pixel)	1-6mm/pixel from 0 to 12 m and 0.7 mrad/pixel (12m+)
Image Noise	RMS < 2% of Full Scale	RMS < 0.5% of Full Scale	RMS <0.5% of Full Scale at <273K
Spectral Range	500 - 900 nm	350 - 950 nm	9 filter positions over expected <400-950 nm range

Table 5 Rover IR Spectrometer Functional Performance

Parameter	Requirement	Desired	Current rover design
Spectral Range	1.0 - 1.6 microns	0.8 - 1.7 microns	0.8 - 1.7 microns
Resolution (accuracy of absorption minima localization)	20 nm	5 nm	3.5 nm/pixel with >3:1 contrast between adjacent pixels, >100:1 over 4 pixels
Noise	RMS < 2% of Full Scale	RMS < 0.3% of Full Scale	RMS < 1% of Full Scale at <233K

Table 6 Rover Alpha X Ray Spectrometer Functional Performance

Parameter	Requirement	Desired	Current rover design
Alpha energy range (MEV)	<0.5 to >5	0.4 (Carbon) to 6 (Fe/Ni)	0.4 to 6
Alpha resolution FWHM	<500 keV	<50keV	~100keV with 2 hour integration at <273K
X-Ray energy range (keV)	<2 to >10	1 to 12	1 to 12
X-Ray resolution FWHM	<1000 eV over spectrum	160-190 eV at 5.9keV line	300 eV at 5.9keV line with 2 hour integration at <273K

Figure 4: Body Internal Configuration